OPTIMIZING MICROGRID DISTRIBUTED ENERGY RESOURCES WITH VARYING BUILDING LOADS: ANALYSIS AND SIMULATION

A Dissertation
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Masters of Science in the
School of Architecture/College of Design

Georgia Institute of Technology
August 2018

OPTIMIZING MICROGRID DISTRIBUTED ENERGY RESOURCES WITH VARYING BUILDING LOADS ANALYSIS AND SIMULATION

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Date Approved: July 26, 2018

To all the pioneers making this world a more sustainable place

ACKNOWLEDGEMENTS

It is with deep gratitude, I express my appreciation for the pivotal role of my advisor, Prof. Godfried Augenbroe. His encouragement, feedback, and overall vision are a source of inspiration. With his support, I began this journey many years ago and am grateful for its continuation. I extend my gratitude to the committee members, Prof. Jason Brown and Bai Blyden. Prof. Jason's thirst for knowledge and for integrative ways to teach and to express have fueled my own work. Bai's expertise and vision of microgrids has been invaluable. I am grateful for the expertise of Suresh Sharma who as entrepreneur in resident at Georgia Tech affirms that changing the world is possible. I thank Gustavo Carneiro for his invaluable feedback on this thesis. Many thanks to Prof. Michael Gamble and Prof. Scott Marble at Georgia Tech who have broadened my vision and manifested our collective vision. I am grateful for many others on this path, Sharrieff, Michael, Bruce, Brian, Mitch, Carol, Bob, Mysty, Chris, Jeff, and others who believe in the vision of a sustainable future for the betterment of all humankind and our planet regardless of color or creed.

Lastly, I express my appreciation to my parents, Max and Amina, for their support throughout the years.

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LIST OF SYMBOLS AND ABBREVIATIONS

BL	Building Load
COE	Cost of Electricity
DG	Demand Generation
DLC	Direct Load Control
DR	Demand Response
DSM	Demand Side Management
EPC	Energy Performance Calculator
EPW	Energy Plus Weather
ESS	Energy Storage System
EUI	Energy Use Intensity
EV	Electric Vehicle
ILC	Interruptible Load Contract
ISO	Independent System Operator
LCOE	Levelized Cost of Electricity
NPC	Net Present Cost
PLM	Power and Light Medium
PV	Photovoltaic
RTO	Regional Transmission Organizations
TMY	Typical Meteorological Year
TOU	Time of Use

SUMMARY

As microgrids continue to evolve and become more prevalent, there arises a need to understand how best to design while addressing the fundamental objective of meeting energy loads. As a localized energy entity, a microgrid brings together distributed energy resources such as photovoltaics and energy storage systems with an array of building loads within a well-defined electrical boundary. Microgrids can vary considerably in scope, co-existing with the utility grid infrastructure, or being able to operate independently of it, or some combination in between of grid-tie and off-grid operation. Many challenges face the design and operation of a microgrid including managing controllers and dispatchers, balancing generation resources, and interacting with the utility grid, all while doing so in a cost-effective manner.

This study examines the role of building load profiles in optimization of distributed energy resources, in particular, photovoltaics and storage systems. For the initial set of scenarios, the grid is assumed to be stable and contrasting rate structures are explored. Similarly, contrasting load profiles shed light on a microgrid's ability to meet demand versus energy loads. Modeling and simulation is done via an industry standard tool, HOMER GRID. Detailed hourly load profiles for various building combinations are generated via an expanded building energy modeling tool, Energy Performance Calculator (EPC), developed at the Georgia Institute of Technology. Any variety of "real-world" representative load profiles can be generated via EPC based on a climate file, building thermal geometry, building parameters, and building usage such as occupancy. EPC includes a mechanism for user-modifiable demand response such as set point temperature

adjustment for the HVAC during peak electricity hours. Optimization is across the spectrum of net present cost, operating cost, return on investment, and a redefined levelized cost of electricity metric.

A simple methodology is derived that can aid in the general design of balancing and optimizing distributed energy resources based on the findings of optimization across scenarios. Of vital importance to a microgrid stakeholder is risk mitigation in the deployment and usage of distributed energy resources, operating costs, and load fulfillment. This study paves the path of better understanding of integration of microgrids within an evolving smarter utility grid.

Further explorations will touch upon the implications of building mix diversity, the effect of electric vehicle (EV) charging stations via the building load profiles, and the evolution of microgrid rate structures from the perspective of Independent System Operators (ISO) and Regional Transmission Organizations (RTO). In addition, scope will be expanded to include microgrids that service villages and islands where grid stability cannot be assumed thus covering the gamut of microgrid presence worldwide.

CHAPTER 1. INTRODUCTION

A microgrid is a means to combine distributed generation (electric, combined heat and power (CHP), or otherwise), building loads and demands, energy storage systems, the regional grid, and algorithms for control, dispatch, and prediction in a way that provides security, resiliency, and financial sense. Accomplishing this tall order is fraught with challenges including the inherently intermittent nature of PV and wind renewable resources, the cost of energy storage systems (albeit with diminishing costs), and the nonlinear, somewhat unpredictable, and dynamic nature of building load demands. In a microgrid, this localized grouping of DG (distributed generation resources) or DER (distributed energy resources), ESS (energy storage systems), and BL (building loads) can operate in conjunction with the grid or can be decoupled from it (Figure 1).

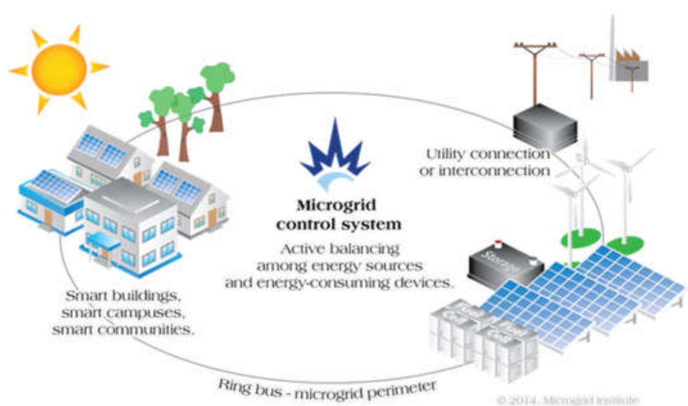

Figure 1: General Microgrid Architecture

Acceptance and deployment of microgrids hinges to a great extent on their means to address local energy problems and their financial viability. This in no small part relies on the mechanisms of control of how all the various resources and loads of the microgrid system are managed (such as centralized, distributed, or hybrid). Typically the aim of a control technique is to stabilize the operation of a microgrid [4]. Here control refers more to the management and dispatch of DER and ESS to match varying BL. Bad decisions in the control mechanisms can lead to financial stress or, worse yet, a partial or complete shutdown of the loads.

Varying energy loads and demand profiles of buildings make for a difficult optimization scenario. Much effort and research has taken place in the generation and control/dispatch side of microgrids. However, a building is not a static entity and its load varies based on a number of factors such as occupancy, temperature control, climate and environmental conditions, and so on. In addition, modern buildings within a smart grid infrastructure have the means to curtail load or demand based on some sort of either direct load control (DLC) or interruptible load contract (ILC).

To influence the electricity usage patterns of customers, there is on-going research in the allied topics of Demand Response (DR) and Demand Side Management (DSM). As stated by the Energy Advantage group on their website [8], "Demand Response is a term used for programs designed to encourage end-users to make short-term reductions in energy demand in response to a price signal from the electricity hourly market, or a trigger initiated by the electricity grid operator". Typically, DR actions would be in the range of a few hours and include turning off or dimming banks of lighting, adjusting setpoint temperatures, or shutting down a portion of a manufacturing process. Alternatively, onsite generation can be used to displace energy drawn from the electricity power grid [9]. In contrast, Demand Side Management focuses on energy efficiency encouraging the end client to make upgrades that could include lighting retrofits, HVAC improvements, and building automation systems. The effects in reduction of demand charges are more enduring but involve more upfront capital investments. These two ideas are represented visually in Figures 2 and 3 [8]. Energy efficiency can produce an overall reduction in power demand; demand response results in short-term reduction of power demand due to load shifting or curtailment.

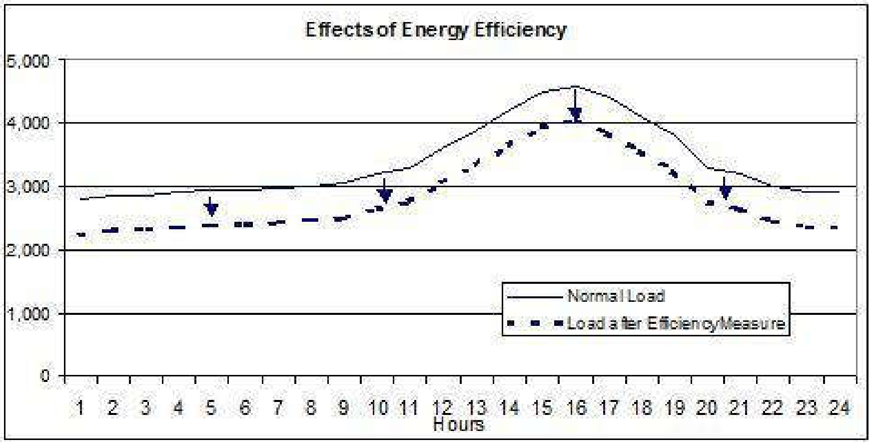

Figure 2: Effects of Energy Efficiency (Demand Side Management)

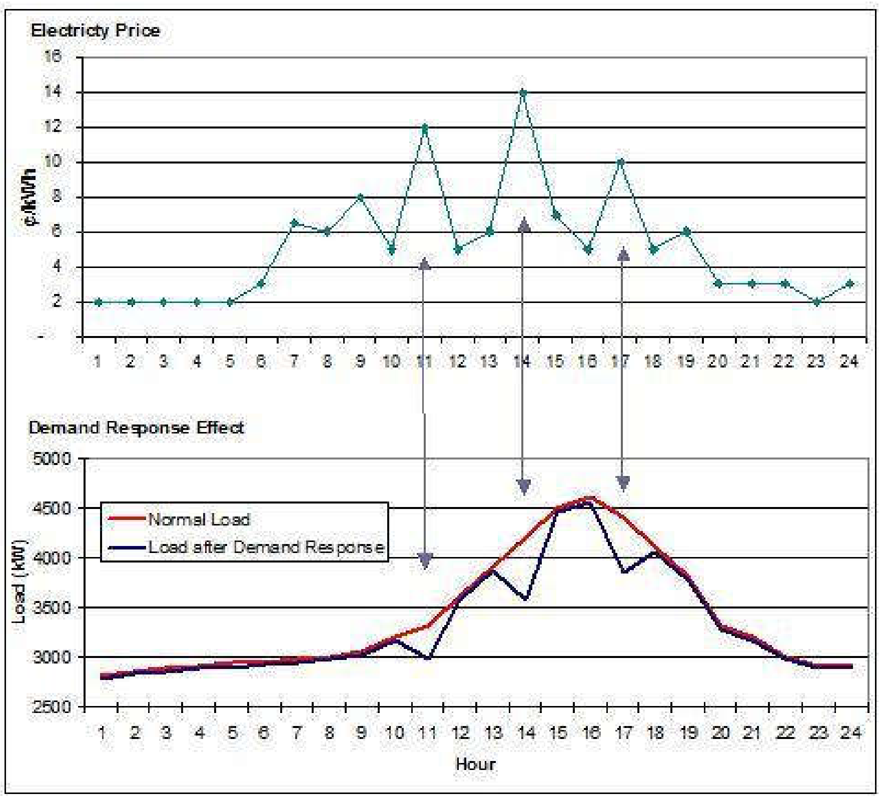

Figure 3: Effects of Demand Response

Both demand response and demand side management techniques are further explored in the paper entitled "A review on micro-grid and demand side management and their related standards" [6] and as illustrated by the following figure and table [6].

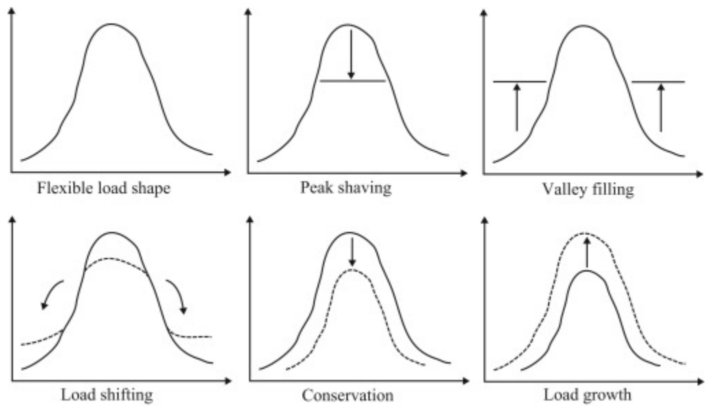

Figure 4: Demand Response and Demand Side Management

Table 1: Demand Response and Demand Side Management

Demand Response and Demand Side Management Techniques	Demand Side Activities
Load Shifting	Shift loads from peak time to off-peak time
Peak Clipping	Reduction of the peak loads
Conservation	Achieve load shape optimization through application of demand reduction methods
Flexible Load	Controlled during critical periods in exchange for various incentives
Valley Filling	Off-peak demand by applying direct load control (DLC)
Load Building/ Load Growth	Increasing demand with processes for constructing

Related to this is the concept of transactive energy management in which smart loads are actively involved in determining the optimal deployment of energy resources. This leads to a "prosumer" topology in which a transactive scheduling optimizer interacts between the energy supplier's offer and a load's bid for energy demand (Figure 5) [3]. Blockchain and other secure mechanisms could be an enabler for viable economic tracking for transactive energy systems. Transactive energy systems and blockchain are beyond the scope of this thesis.

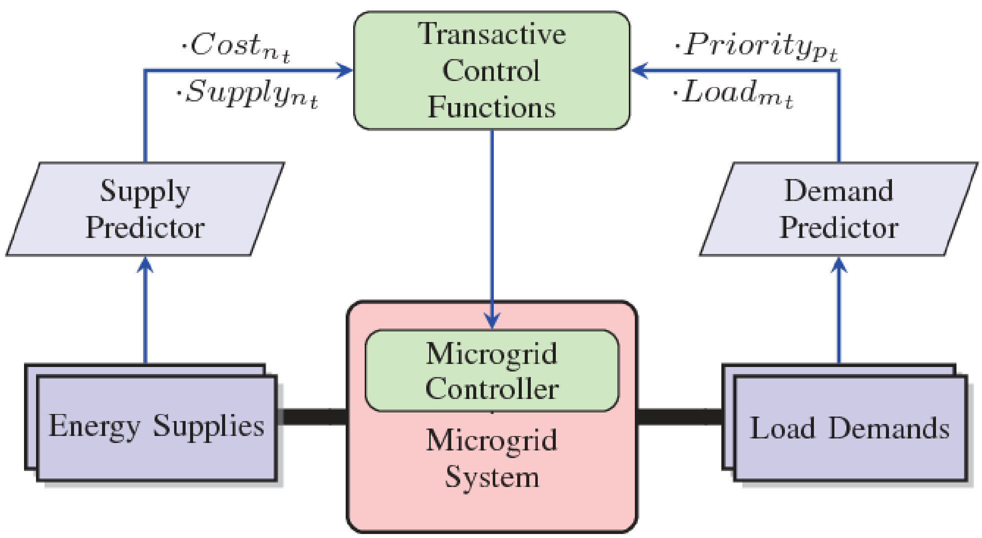

Figure 5: Transactive Energy Systems

Microgrids are not unique in adding intelligence and communication between loads and generation via a controller. Utilities have been exploring the role of such systems and protocols within the context of a smart grid. The advent of digital communication, sophisticated sensors, smart meters, and load devices with some level of intelligence allow for two-way communication between the utility and its customers. Utilities incur many benefits with such technology including the following as per a government research site on smart grids [9]:

- More efficient transmission of electricity
- Quicker restoration of electricity after power disturbances
- Reduced operations and management costs for utilities, and ultimately lower power costs for consumers
- Reduced peak demand, which will also help lower electricity rates
- Increased integration of large-scale renewable energy systems
- Better integration of customer-owner power generation systems, including renewable energy systems
- Improved security

Microgrids share many of the aforementioned benefits with smart grids, but differ in that they can disconnect from the greater grid and can address the issues within a contained boundary or collection of understood and localized loads. In microgrids, renewable energy resources are typically distributed rather than centralized.

Microgrids can vary tremendously in complexity based on what they are serving. For example, a microgrid situated in a modern day industrial city featuring complex campus building loads typically relies on a stable grid. Another situated in a developing nation with simpler and more distributed buildings in a rural setting would be expected to run more “off-grid”. A grid situation on a modern island may benefit from some level of grid sophistication but the cost of generation may be high (diesel, oil, etc) or may suffer from brownouts or short blackouts. These terms capture the relationship between the three scenarios: smart city, smart village, and smart island. The smart city approach entails connecting to the larger prevalent grid and with a diversity of ac loads some of which have built-in intelligence; the smart village approach may mean a smaller collection of loads (both dc and ac) with minimally developed economic infrastructure. For a smart island, a hybrid approach is required in which the grid is present but distributed energy resources can help mitigate the expense and extend the reliability. The grid remains the core of a smart city approach whereas the focus is on the distributed energy resources for the smart village.

CHAPTER 2. PROBLEM STATEMENT

The load profile of a microgrid has a key influence on its optimization whereby the demand side drives the generation and control side. A complex and varying load profile can affect numerous parameters making up the microgrid. By some estimates, buildings account for more than 40% of electrical usage in the United States [11]. Similarly, buildings constitute the bulk of loads for microgrids. Understanding the demand side portion of the microgrid equation is therefore vital for an effective design.

This thesis explores the impact and influence of the variability in electrical energy demand of building loads for the optimization design and operation of a microgrid. Patterns that can be discerned across different building profiles, rate structures, and other parameters can help in designing microgrid configurations and in shedding light on the key areas to focus on. Ideally, a methodology can be derived to design optimized microgrids under load and renewable generation uncertainties. Microgrid designers and operators generally seek to mitigate risks in deployment and usage of distributed energy resources, operating costs, and meeting load needs (Figure 6).

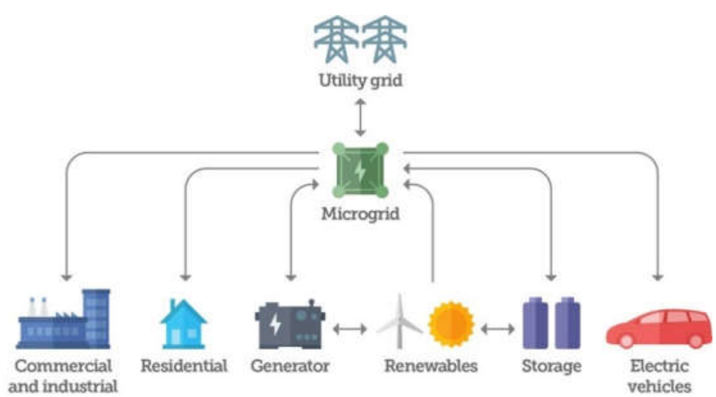

Figure 6: Balancing Microgrid Resources

An advanced microgrid can incorporate aspects of a utility smart grid such as demand response in which loads can adjust in real time through curtailment, deferment, or other mechanisms. Modeling this tends to be more difficult. Real time dynamic modeling (two-way communication between the controller and the building loads) will not be addressed immediately in this thesis. Future research can focus on extending the toolsets to allow dynamic modeling. Similarly, future work can extend to modeling and deriving patterns for smart villages and for smart island scenarios.

In focusing on the electric needs, numerous scenarios are explored with some key questions. The first few consist of zero order comparative analysis in which there is no real time modification of the load profile (zero energy flexibility); the latter simulations will entail simulated demand response throttle setback (energy flexibility). In some sense, these simulations get progressively more complicated building on earlier work. All these simulations serve to answer the basic question of how does building mix matter. This question leads to the following:

How does building load profile change the optimization of the microgrid?

How does demand response affect the microgrid?

Does shifting the demand response provide a visible benefit?

How does adding intermittent loads such as EV charging the optimal configuration of the microgrid?

What patterns can be discerned and how might that influence the optimal configuration of a microgrid?

CHAPTER 3. METHODOLOGY

Modeling and optimizing a microgrid entails numerous considerations. A microgrid placed in a city with a stable grid (“smart city microgrid”) will be constructed somewhat differently than one situated in an area with an unstable grid (“smart village microgrid”). Utility rate tariff structures can shape the cost-effectiveness of a microgrid. Different load profiles represent differences among buildings. Distributed energy resources consist of photovoltaics and/or energy storage systems with the appropriate converter/inverters. Overall economic parameters must be considered such discount rate, inflation rate, and project lifetime in years. Costing for all components is vital.

Various tools exist for modeling a microgrid system completely or in key aspects. The System Advisor Model (SAM) from NREL, HOMER PRO, HOMER GRID, EnergyToolbase and others are some that are available. These are chronological simulations that walk through each timestep of a year (such as 8760 annual hours) in which a controller/dispatcher optimizes decisions based on user-entered parameters that result in the lowest net present cost (NPC) or the greatest system internal rate of return (IRR).

These tools provide a lot of flexibility in modeling the renewable energy source (PV, wind, battery, etc), the grid side, and the interconnecting topology. However, they are typically somewhat limited in modeling the demand side, allowing for one load profile – or in the case of HOMER GRID and HOMER PRO, a critical and non-critical load profile. The load profile can be entered as a time-varying series with all 8760 hours accounted for. However, once the values are entered they cannot change dynamically in any way during simulation itself. The load is either met or it is not. Since the current tools allow only for a single load profile, only a single grid tariff can be used for the entire microgrid. For that reason, the microgrid is assumed to connect to the utility with a single meter. The utility rate tariff structure applies to all consumers in the microgrid.

Different load profiles will of course result in variations in the microgrid optimization. Much work has been done in control algorithms and microgrid topologies (cite references here). However, traditionally in the research not quite as much focus has been placed on the demand side and the analysis of the effect of a mixture of building profiles. This thesis explores how variations in load profiles affect the viability of microgrids. A standardized and common topology is kept amongst all scenarios with all variability contained within the load profile. HOMER PRO and HOMER GRID are used to model the microgrid. Due to aforementioned behavior of how a load is handled in HOMER, individual building load profiles are aggregated together (as if they were sharing a single meter) before being fed into the simulator.

How the microgrid controller responds depends on the minute by minute power variations of the loads. A load profile consists of multiple energy consumers such as HVAC systems, lighting, plug-loads, and so on. Together they form a composite load profile for a building. Typically, a utility meter is paired with a building. For a commercial situation, the building is billed based on the total energy consumed per month in kilowatt-hours (as a measure of energy) and the excess power above a certain agreed upon threshold in kilowatts (as a measure of power). The latter is called “demand charge” and is the cost charged by the utility associated with the “surge” that it has to meet in terms of bringing up potentially additional power generation facilities. The key to a microgrid is the control technology that is able to manage the varying loads and diverse power/energy sources within a well-defined boundary or general topology.

Realistic load profiles are created using the Energy Performance Calculator (EPC) developed at Georgia Tech. EPC is a tool that has been vetted over tens of thousands of runs. It is typically used to derive an EUI (Energy Use Intensity) which indicates the delivered energy consumption per unit area or how efficient a building is based on its composition, construction, anticipated usage, and location. EPC aims to predict future "typical" energy behavior of a building by reading in a climate file based on a TMY (Typical Meteorological Year) or EPW (Energy Plus Weather). For this thesis, a variant of the tool has been created that generates a full 8760 hour electric usage load profile subtracting out any entered natural gas usage (such as for the HVAC heating and/or domestic hot water). The tool variant also allows for combining different types of load profiles to create an aggregate consisting of multiple buildings. Finally, demand side response can be simulated by allowing the cooling set point temperature to float during critical summer days.

Four scenarios are explore. Initial scenarios involve zero order comparative analysis in which there is no real time modification of the load profile (zero energy flexibility); latter scenarios entail simulated demand response throttle setback (energy flexibility). All these simulations serve to answer the basic question of "how does mix matter?"

How does building profile mix change the optimization of the microgrid? How does demand response affect the microgrid? Does shifting the demand response provide a visible benefit? How does adding EV charging affect the optimum configuration?

1. A load profile consists of identical buildings such as a medium sized office or residential apartment buildings. In both cases, the aggregate load is simply a linear multiplication of the individual derived loads. Key differences between a commercial load and a residential load relate to both the energy usage hours and the presence of demand charges.
2. A mixed load profile is derived consisting of two scenarios: 90% commercial and 10% residential in one case and 10% commercial and 90% residential in the other case.
3. Load profile consists of a collection of community buildings representing a more realistic mix as would be found in real world microgrid.
4. Energy flexibility in which there is an energy setback during critical load days (such as where peak load exceeds a threshold). This can be achieved through the building profile generator by increasing the temperature during peak electricity hours (e.g. 2 PM to 6 PM during the summer critical load days) such as the air conditioning system does not work as hard during set times. For realism, a maximum temperature delta of 2.5 Celsius should not be exceeded. For additional realism, a penalty function should be added for potential damage due to some productivity loss due to the higher afternoon temperature.
5. A future scenario would involve the addition of semi-randomized EV charging to one of the previous load profiles.

CHAPTER 4. LOAD GENERATION

Generating a representative load is an elaborate process requiring accurate modeling of a building. The US Department of Energy in the Open Data Catalog have hourly load profiles for different types of buildings across almost any major city in the United States. While these are useful, the loads are "pre-canned" and so do not easily allow for handling of demand response or other functions. Nonetheless, the database was consulted to derive representative building parameters for entry into a custom load generator (Table 2). Microgrid location is set to Atlanta, GA, USA with a respective TMY3 climate file (Typical Meteorological Year).

Table 2: Building Categories and Representative Buildings

BUILDING NUMBER	BUILDING CATEGORY	BUILDING TYPE NAME	TOTAL FLOOR AREA (FT^2)	TOTAL FLOOR AREA (M^2)	NUMBER OF FLOORS	ANNUAL LOAD (FROM EPC) (kWh)	DAILY AVERAGE LOAD (FROM EPC) (kWh)
1	Commercial	Large Office	498,588	46,320	12		
2	Commercial	Medium Office	53,628	4,982	3	701,731	1,923
3	Commercial	Small Office	5,500	511	1		
4	Commercial	Warehouse	52,045	4,835	1		
5	Retail	Stand-alone Retail	24,962	2,319	1		
6	Retail	Strip Mall	22,500	2,090	1		
7	Educational	Primary School	73,960	6,871	1		
8	Educational	Secondary School	210,887	19,592	2		
9	Retail	Supermarket	45,000	4,181	1		
10	Retail	Quick Service Restaurant	2,500	232	1		
11	Retail	Full Service Restaurant	5,500	511	1		
12	Medical	Hospital	241,351	22,422	5		
13	Medical	Outpatient Health Care	40,946	3,804	3		
14	Civil	Small Hotel	43,200	4,013	4		
15	Civil	Large Hotel	122,120	11,345	6		
16	Commercial	Midrise Apartment	33,740	3,135	4	597,246	1,636

Two of these buildings represent a good cross-section of load profiles: medium office and midrise apartment. A commercial office has a load profile that is day-centric with little activity in the evenings, nights, and weekends; in contrast, a residential or apartment building has a load profile that is morning, evening, and weekend centric with little activity during core working hours of a weekday.

Buildings consume energy: electrical, natural gas, and otherwise. A building performance tool, Energy Performance Calculator (EPC), has been developed over the years for detailed energy modeling of any type of building with extensive parameter entry including but not limited to climate file, building orientation, building thermal envelope, mechanical systems, and building usage including occupancy and hourly set point temperatures (Figure 7). This tool was extended and customized to derive electrical hourly load profiles (Figures 8 & 9). Further modifications allow it to simulate demand response but adding a temperature delta to allow the temperature to float for air conditioning during any specified hours (thus allow the HVAC system to back down selectively).

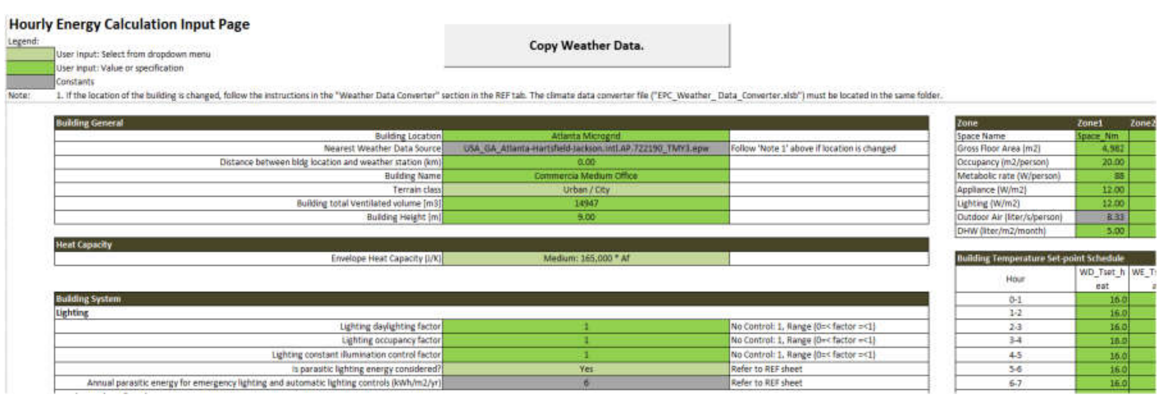

Figure 7: EPC Parameter Entry

Gross Floor Area			Area (m2)	4,982		
						Load Factor:
Delivered Energy						
Month	Date	Day Hour	Yearly Hour	Etotal [W/m2]	Electric Load [kW]	Electric Load x Load Factor [kW]
Jan	1	1	1	3.31	16.47	164.69
Jan	1	2	2	3.31	16.47	164.69
Jan	1	3	3	3.31	16.47	164.69
Jan	1	4	4	3.31	16.47	164.69
Jan	1	5	5	3.31	16.47	164.69
Jan	1	6	6	3.31	16.47	164.69
Jan	1	7	7	3.31	16.47	164.69
Jan	1	8	8	3.31	16.47	164.69
Jan	1	9	9	3.31	16.47	164.69
Jan	1	10	10	3.31	16.47	164.69
Jan	1	11	11	3.31	16.47	164.69
Jan	1	12	12	3.31	16.47	164.69
Jan	1	13	13	3.31	16.47	164.69
Jan	1	14	14	3.31	16.47	164.69
Jan	1	15	15	3.31	16.47	164.69
Jan	1	16	16	3.31	16.47	164.69
Jan	1	17	17	3.31	16.47	164.69
Jan	1	18	18	3.31	16.47	164.69
Jan	1	19	19	3.31	16.47	164.69
Jan	1	20	20	3.31	16.47	164.69
Jan	1	21	21	3.31	16.47	164.69

Figure 8: EPC Hourly Load Generation

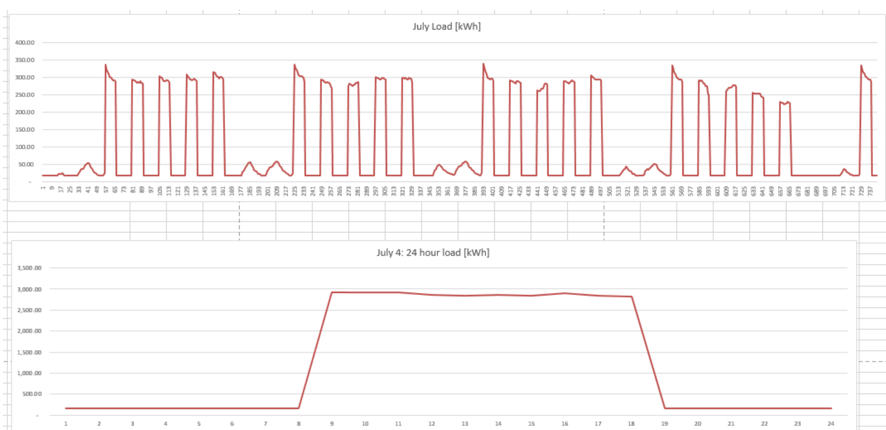

Figure 9: EPC Hourly Generation Graphic

A microgrid load portfolio consist of multiple building loads. EPC has been extended to generate a mixture of any number of building by summing together the hourly load profiles. Since most simulation require an aggregated load profile, EPC will generate the composite load profile based on requested building mix.

The commercial load profile consists of 10 mid-size office buildings (Figure 10).

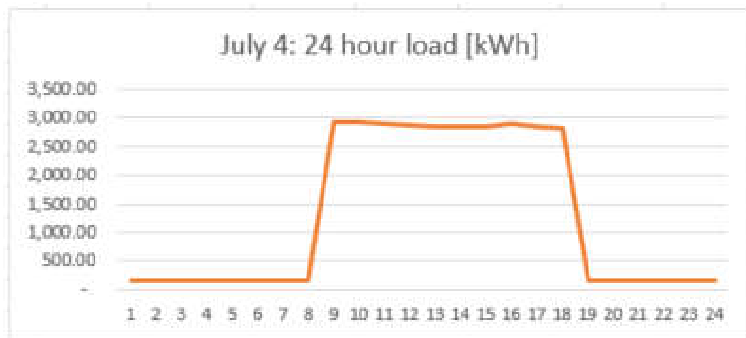

Figure 10: Commercial Load Profile

The apartment complex load profile consists of 10 midrise apartments (Figure 11).

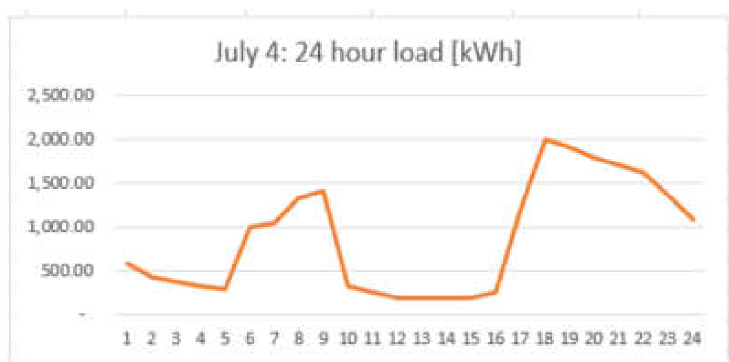

Figure 11: Residential Apartment Complex

The mixed building load consists of 5 midrise apartment building combined with 5 medium office buildings. It's a marriage of a commercial and a residential load profile (Figure 12).

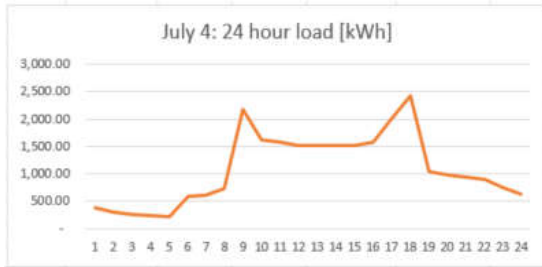

Figure 12: Mixed Building (Commercial and Resi Apartment)

Demand Response is simulated within EPC by using a delta of 2.5 Celsius on the cooling temperature set point from 2 PM to 6 PM to mitigate demand during the critical days of the summer months of June, July, August, and September (Figures 13 and 14).

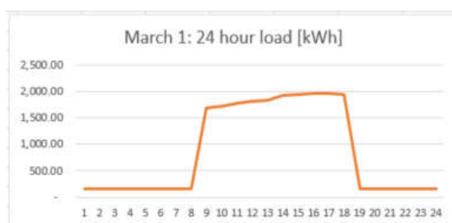

Figure 13: Commercial Spring/Winter without Demand Response

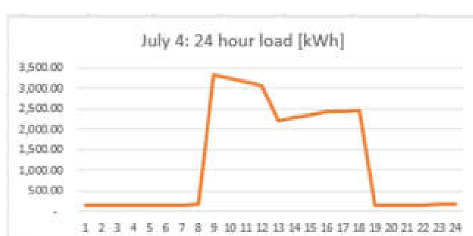

Figure 14: Commercial Summer Month with Demand Response

For ease of comparison, the annual aggregated load in kWh among all profiles is similar.

CHAPTER 5. RATE STRUCTURE

Rate tariffs have a significant impact on how and when a microgrid draws upon utility grid power. Numerous rate structures exist but two that are on opposite poles of the tariff spectrum are time of use (TOU) and flat rate. Variants of flat rate structures include tiered where additional energy above predetermined thresholds is charged at a lower bracket. Often TOU rates consist of both the consumption rate of actual energy consumed each hour and a demand charge calculated hourly. Flat rate structures often have an overall higher starting energy charge but remain consistent with minimal demand charge.

Since the location of the microgrid is selected to be in Atlanta, Georgia, tariff schedules from the largest State utility, Georgia Power, are used.

The Georgia Power TOU-GSD-10 tariff is defined in three intervals of on-peak (2PM to 7PM), shoulder (12 noon to 2PM), and off-peak (all other times). Peak times are during the months of June, July, August, and September. The difference in energy cost per kWh is over 5-fold (from 2.4 cents to 12.2 cents) and over 3-fold in demand charge cost (from \$5.23 to \$15.66 per kW) (Figures 15 & 16) (Appendix C).

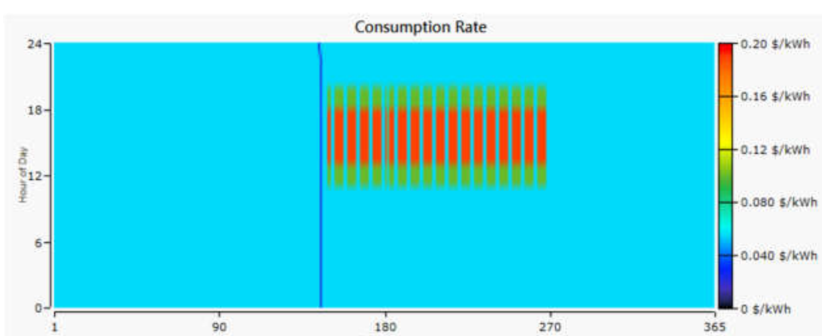

Figure 15: TOU-GSD-10 Consumption Rate

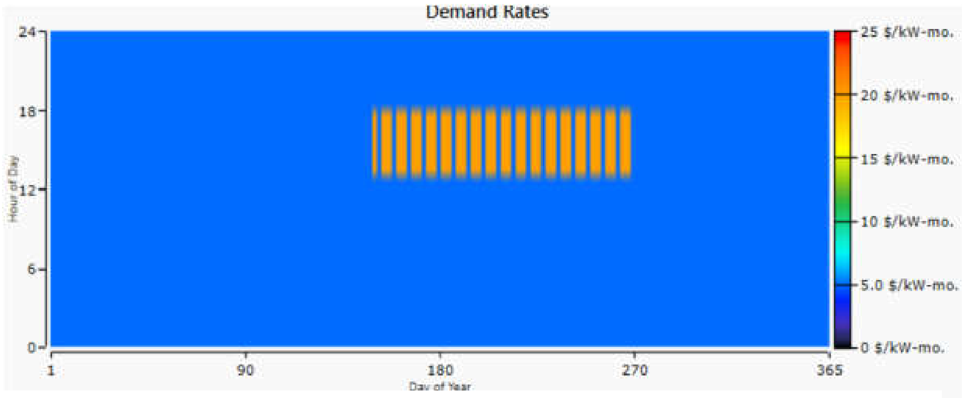

Figure 16: TOU-GSD-10 Demand Rate

In contrast, Georgia Power's tiered tariff schedule such as Power and Light Medium (PLM-11) is more uniform (Figures 17 & 18) (Appendix B).

Figure 17: PLM-11 Consumption Rate

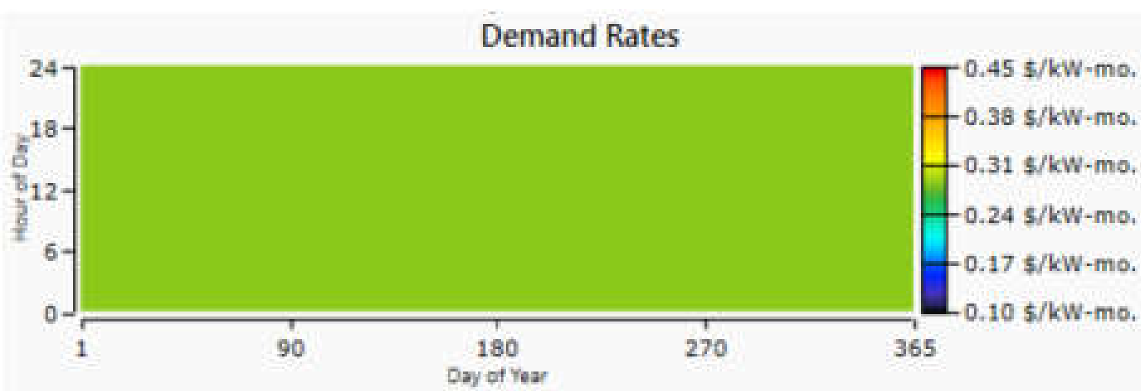

Figure 18: PLM-11 Demand Rate

The intent of renewable energy resources is to serve the local captive loads. However, at times, the renewables generate surplus. This surplus can be stored in batteries (depending on how many are designed in) or sold back to the grid. HOMER GRID allows for true net metering in which electricity is sold back at the same rate that it is purchased. However, utilities vary considerably in permitting sell-back of any generated electricity. To this end, the sell-back will be capped to around 10% of bought energy. In addition, zero sell-back and full-sell back will be explored.

As utilities contend with the growth of microgrids, they will arrive at newer rate structures that are better suited for microgrids. This is an ongoing area of exploration by Independent System Operators (ISO) and Regional Transmission Organizations (RTO) whose purpose is to promote economic efficiency and reliability in the overall grid network. In some sense, there is a push-pull relationship between microgrid operators and the utility provider. Microgrids are motivated to provide localized (captive) energy in an efficient and cost-effective and reliable way with consideration of the economics of the utility tariffs. So current utility rate structures may encourage microgrids to generate more of their own energy through distributed renewable means. However, the greater the success of microgrids, the more a utility may be motivated to create a rate structure that dissuades grid defection. Deriving rate structures that are suited for microgrids is an on-going area of research. This study does not address the question of tariff evolution.

CHAPTER 6. PROCEDURE

Using HOMER GRID, for a grid-connected system a standard topology is established with two busses to connect the various components (Figure 19). The utility grid is connected to an AC bus along with the aggregate load. In addition, the PV array is also connected there (via inverters). A converter (battery inverter) connected a selection of two types of batteries: a Tesla 210 kWh PowerPack2 and a generic 100kWh lithium pack.

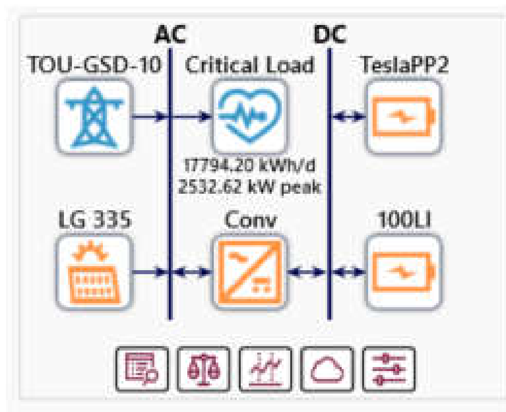

Figure 19: Topology for HOMER GRID

All three distributed resources are variable in that the PV array, the Energy Storage System #1, and the Energy Storage System #2 are allowed to float within a range as shown in Table 3. The two Energy Storage Systems are modeled as mutually exclusive so when one is a non-zero value, HOMER sets the other to be zero.

Table 3: Component Range

Component	Unit Size	Optimization Range (Quantity)	Optimization Range (Value)
PV LG335 array	335 W	0 to 29,850	0 to 10 MW
Tesla PowerPack2 (210 kWh)	210 kWh	0 to 50	0 to 10.5 MWh
Generic 100kWh lithium	100 kWh	0 to 30	0 to 3 MWh

Pricing for each component is based on established values for real PV systems as being installed in the southern states of the United States. Prices do vary based on system size, complexity, and regional differences [Table 4]. HOMER GRID allows for a cost function based on system size.

Table 4: Component Pricing

Component	Initial cost	Unit Size	Cost per Unit (per kWh)	Lifespan (years)	Replacement cost
PV LG335 array	10 kW -> $19,000 100 kW -> $150,000 1000 kW -> $1,400,000 3000 kW -> $3,750,000	10 kW 100 kW 1000 kW 3000 kW+	10 kW -> $1.90/W 100 kW -> $1.50/W 1000 kW -> $1.40/W 3000 kW+ -> $1.25/W	25	10 kW -> $19,000 100 kW -> $150,000 1000 kW -> $1,400,000 3000 kW -> $3,750,000
Tesla PowerPack2 (210 kWh)	$75,000	210,000	$357.14	10	$75,000
Generic 100kWh lithium	$40,000	100,000	$400.00	10	$40,000

A load profile is generated within EPC and imported as a time-series dataset.

With the PV system size and ESS sizes allowed to float, HOMER GRID will explore the parameter space to derive solutions that present various financials for each combination of design: net present cost (NPC), cost of electricity (COE), operating cost ($/yr), and initial capital cost ($).

LCOE is a powerful metric used to "compare the relative cost of energy produced by different energy-generating sources, regardless of the project's scale or operating time frame." Typically it is a "source" or "generation" metric in which the cost to generate power by traditional utility means such as via natural gas or hydro can be compared to renewable means of generating the same power (such as by wind, solar, tidal, or biomass). It allows for an "apples-to-apples" comparison.

The fundamental formula for source/generation LCOE is simply this:

LCOE = Total Life Cycle Cost / Total Lifetime Energy Production

The Total Life Cycle Cost includes construction costs (CapEx) and lifetime operational cost (OpEx). It may also include any salvage or residual value at the end of the project's lifetime. Incentives can be factored in as well. Once a project lifetime is established then the total lifetime energy production can be determined including accounting for any annual production degradation.

HOMER defines the Cost of Electricity (COE) metric somewhat differently. Rather than a being associated with the "source" or "generation", it refers to the "load". It is also annualized rather than taken over the system lifetime. It is more akin to an effective blended cost of electricity in which the annual operating cost factors in the mix of all costs of electricity such as total purchases from the grid (which include energy and demand charges) and the amortized cost of the distributed energy resources. It cannot be used to compare to the LCOE derived the traditional way which address source level generation costs.

HOMER COE = total annualized cost of the system / total annual electrical load served

Within the provided range for each component, HOMER runs through thousands of simulations. HOMER optimizes the Net Present Cost (NPC) within each category and then sorts across categories so different scenarios can be compared. Simulation results for the entire parameter space can be viewed to glean further insight. Optimization is achieved when the NPC is lowest within a category; the full collection of other parameters can be examined such COE, IRR, operating cost, utility energy savings.

Within this topology and the varied parameters, six optimization categories are established: PV only, ESS#1 only, ESS#2 only, grid-only, PV+ESS#1, PV+ESS#2.

CHAPTER 7. RESULTS

Within the context of the "smart city" microgrid, adding distributed energy resources increases the value proposition of scenarios across all load profiles. This comes as no surprise due to the significant reduction in PV pricing over the last few years. Energy Storage pricing is following suit but typically ESS alone can be still a difficult sell; however, when combined with PV (to allow storage to be charged from renewables), it can result in overall savings particularly when demand charge reduction is factored in. The nature of the benefits based is nuanced based on the scenarios.

A comparative analysis across the four very different load scenarios and across each of the two different tariff rates shows an interesting trend. Considering just the baseline grid-only operating cost, certain rate tariffs result in a lower operating cost matching the usage profile (Figure 20). For example, Time of Use (TOU) penalizes usage (both demand and energy) during certain peak hours. In the case of TOU-GSD-10, afternoon usage is heavily billed. So a load profile such as a commercial one favoring afternoon usage is seen to be better off with a tiered flat rate structure such as Power and Light (PLM) (a full 10% less with Commercial PLM compared with Commercial TOU).

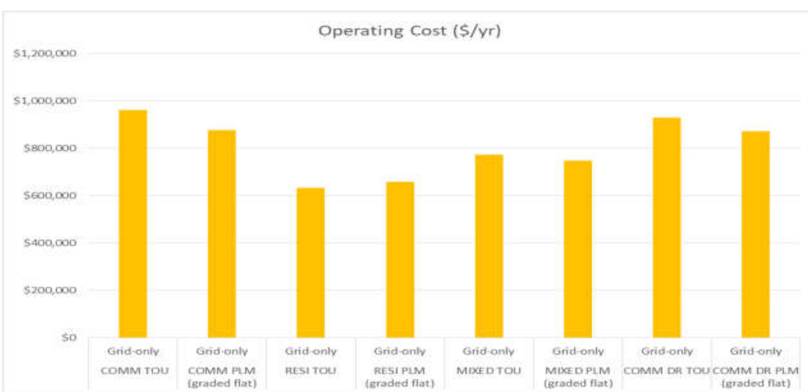

Figure 20: Baseline Grid-only Operating Cost

Table 5: Grid-Only Operating Costs

		Architecture		*Cost*		
Building Mix	Rate Schedule	*Option*	Average Load (kWh/day)	NPC ($)	COE ($)	Operating Cost ($/yr)
Commercial	COMM TOU	Grid-only	19,225	$16,865,980	$0.137	$962,240
Commercial	COMM PLM (graded flat)	Grid-only	19,225	$15,396,290	$0.125	$878,391
Residential	RESI TOU	Grid-only	16,362	$11,106,450	$0.106	$633,646
Residential	RESI PLM (graded flat)	Grid-only	16,362	$11,561,440	$0.110	$659,605
Com 50% and Resi 50%	MIXED TOU	Grid-only	17,794	$13,579,300	$0.119	$774,728
Com 50% and Resi 50%	MIXED PLM (graded flat)	Grid-only	17,794	$13,134,070	$0.115	$749,327
Com DR 2 to 6PM	COMM DR TOU	Grid-only	18,957	$16,306,170	$0.134	$930,301
Com DR 2 to 6PM	COMM DR PLM (graded flat)	Grid-only	18,957	$15,305,530	$0.126	$873,213

Any demand response on a profile that alleviates peaks (or shifts them) during key hours can result in substantial savings. As per Table 5, a 1% reduction in average daily load focused during peak hours along with an accompanied demand response and shift of demand to after 6 PM results in an almost 3.5% operating cost savings ("Commercial" vs "COM DR 2 to 6PM") with the TOU rate. As expected, no such savings are seen when comparing operating cost usage for the tiered flat rate PLM rate structure between "Commercial" and "Commercial with Demand Response".

A residential profile that favors consumption outside of peak hours can benefit from a time of use rate. That is seen in this case with the TOU operating cost coming in 4% less than a tiered flat rate (PLM). The residential profile peaks in the morning and between 6 to 7 PM and then slowly declines in usage until midnight. A TOU rate structure that doesn't penalize early morning or early evening hours will prove beneficial to a residential load profile.

For a blended profile consisting of both commercial and residential load profiles (such as the 50% blend), the operating cost delta between a TOU rate and a PLM rate is reduced (4% less for the PLM vs the TOU rate). PLM is still the preferred rate plan since consumption is at a steady rate throughout the afternoon which TOU would penalize.

Addition of a PV-only system results in high gains across all scenarios regardless of the rate plan. Since the total install price of a PV system has reduced to below \$2/Watt throughout much of the United States (for systems larger than 50 kW and even less for larger systems), the benefits of PV are immediate. For a commercial system, simulations result favor large PV systems with a high renewable fraction (more than 50%). Payback is well under 10 years in these cases. More than 50% operating cost savings are possible for both TOU and PLM (Table 6).

Table 6: PV+Grid Comparisons

Building Mix	Rate Schedule	*Option*	Average Load (kWh/day)	PV Size (kW)	Operating Cost (\$/yr)	Renewable Fraction (%)	IRR (%)	Simple Payback (yr)	Utility Bill Savings (\$/yr)
Commercial	TOU	PV-only (with Grid)	19,225	5625	\$327,486	66.6	11.3	7.9	\$458,487
Commercial	PLM (graded flat)	PV-only (with Grid)	19,225	6145.8	\$144,800	68.8	12.4	7.3	\$541,378
Residential	TOU	PV-only (with Grid)	16,362	1250	\$506,062	21.1	7.5	10.8	\$85,261
Residential	PLM (graded flat)	PV-only (with Grid)	16,362	625	\$594,947	13.7	7.1	11.2	\$43,377
Com 50% and Resi 50%	TOU	PV-only (with Grid)	17,794	3385.4	\$394,433	49.1	10.8	8.2	\$272,594
Com 50% and Resi 50%	PLM (graded flat)	PV-only (with Grid)	17,794	3854.2	\$337,168	51.6	10.0	8.7	\$290,107
Com DR 2 to 6PM	TOU	PV-only (with Grid)	18,957	5208.3	\$349,548	64.2	11.0	8.1	\$417,243
Com DR 2 to 6PM	PLM (graded flat)	PV-only (with Grid)	18,957	6041.6	\$142,053	68.1	12.7	7.2	\$542,136

The yearly **distribution** of the **cost** of electricity based on tariff rate also impacts the optimized PV system size and any subsequent annual benefits. That is, even if the load profile is comparable for each month, the cost incurred may not be based on difference in tariff rate throughout the year. Case in point, the following figures show the electricity cost variation due to tariff structure. The optimizer opts for a larger PV system for the PLM that offsets more “expensive” grid-purchased energy year around (not just the summer months) resulting in less overall **annual** purchases of grid electricity. So optimization decisions are based not just on peak days or months but a full assessment of the yearly behavior. The complete monthly purchased grid electricity breakdowns are provided in Figures 21 and 22 and Tables 7 and 8.

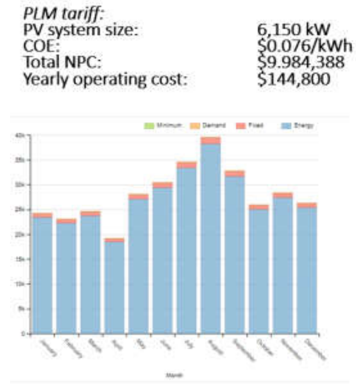

Figure 21: Commercial PLM with PV+Grid monthly cost

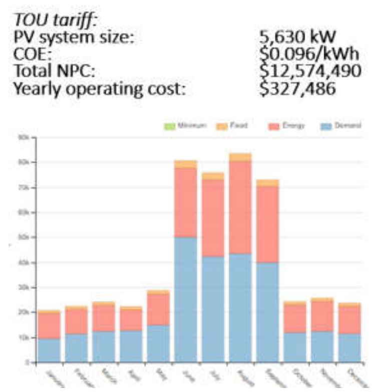

Figure 22: Commercial TOU with PV+Grid monthly cost

Table 7: Commercial yearly electricity cost distribution (TOU)

Electrical Bill (Predicted): System #2

Tariff: General - Time of Use, Demand

	January	February	March	April	May	June	July	August	September	October	November	December
Energy Charges, Consumption, and Sales	$10,052	$9,695	$10,356	$8,301	$12,316	$27,575	$30,632	$36,920	$30,336	$11,027	$11,926	$10,847
	172,368 kWh	166,247 kWh	177,732 kWh	143,105 kWh	213,269 kWh	231,364 kWh	264,800 kWh	307,343 kWh	245,054 kWh	190,099 kWh	205,425 kWh	186,996 kWh
	36,809 kWh	34,070 kWh	46,789 kWh	47,672 kWh	43,494 kWh	39,465 kWh	40,188 kWh	34,963 kWh	35,952 kWh	42,782 kWh	36,147 kWh	37,620 kWh
Demand Charges and Peak Demand	$9,491	$11,400	$12,401	$12,711	$14,920	$50,088	$42,297	$43,482	$39,909	$11,906	$12,381	$11,528
	1,815 kW	2,180 kW	2,371 kW	2,430 kW	2,853 kW	3,053 kW	2,701 kW	2,777 kW	2,541 kW	2,276 kW	2,367 kW	2,204 kW
Fixed charges ($)	$1,154	$1,200	$1,250	$1,195	$1,382	$2,894	$2,752	$2,976	$2,671	$1,253	$1,294	$1,236
Monthly Total	$20,697	$22,296	$24,006	$22,207	$28,617	$80,557	$75,681	$83,378	$72,916	$24,186	$25,601	$23,611
Annual Total	$503,753											

Table 8: Commercial yearly electricity cost distribution (PLM)

Electrical Bill (Predicted): System #1

Tariff: Medium Power & Light

	January	February	March	April	May	June	July	August	September	October	November	December
Energy Charges, Consumption, and Sales	$23,422	$22,278	$23,759	$18,485	$27,127	$29,394	$33,396	$38,249	$31,672	$25,057	$27,399	$25,395
	165,929 kWh	157,747 kWh	168,503 kWh	131,757 kWh	194,941 kWh	209,488 kWh	243,699 kWh	285,196 kWh	228,963 kWh	179,140 kWh	197,165 kWh	181,579 kWh
	37,523 kWh	35,473 kWh	48,717 kWh	50,198 kWh	46,483 kWh	42,636 kWh	44,057 kWh	38,160 kWh	37,971 kWh	45,544 kWh	37,248 kWh	38,526 kWh
Demand Charges and Peak Demand	$78	$94	$104	$104	$124	$133	$117	$121	$111	$98	$104	$97
	1,792 kW	2,157 kW	2,367 kW	2,372 kW	2,826 kW	3,027 kW	2,678 kW	2,760 kW	2,539 kW	2,242 kW	2,366 kW	2,204 kW
Fixed charges ($)	$729	$695	$740	$582	$841	$910	$1,029	$1,175	$977	$779	$849	$789
Monthly Total	$24,230	$23,068	$24,603	$19,170	$28,092	$30,437	$34,542	$39,545	$32,761	$25,933	$28,352	$26,280
Annual Total	$337,013											

Since PV production coincides to daytime usage of a commercial profile, the optimizer yields the largest systems in such cases (including for blended building scenarios). When demand response (DR) is implemented for a commercial scenario then a somewhat smaller PV system suffices and, as expected, the demand charge savings are reduced (but savings on the energy portion are consistent). For a residential load profile, usage patterns dictate a smaller PV system (since sellback is limited) during the day. Table 9 compares the PV+Grid scenarios (without ESS).

Table 9: PV+Grid Comparisons

		Architecture				*Cost*				*System*		*Economics*				
Building Mix	**Rate Schedule**	***Option***	**Average Load (kWh/day)**	**PV Size (kW)**	**ESS Size (kWh)**	**NPC ($)**	**COE ($)**	**Operating Cost ($/yr)**	**Initial Capital ($)**	**Renewable Fraction (%)**	**N/A**	**IRR (%)**	**Simple Payback (yr)**	**Utility Bill Savings ($/yr)**	**Demand Charge Savings ($/yr)**	**Energy Charge Savings ($/yr)**
Commercial	TOU	PV-only	19,225	5625		$12,574,490	$0.096	$327,486	$6,834,375	66.6	0	11.3	7.9	$458,487	$58,364	$400,123
Commercial	PLM (graded flat)	PV-only	19,225	6145.8		$9,984,388	$0.076	$144,800	$7,446,354	68.8	0	12.4	7.3	$541,378	$247	$541,131
Residential	TOU	PV-only	16,362	1250		$10,563,910	$0.096	$506,062	$1,693,750	21.1	0	7.5	10.8	$85,261	$9,488	$75,773
Residential	PLM (graded flat)	PV-only	16,362	625		$11,307,300	$0.105	$594,947	$879,167	13.7	0	7.1	11.2	$43,377	$33	$43,344
Com 50% and Resi 50%	TOU	PV-only	17,794	3385.4		$11,116,410	$0.092	$394,433	$4,202,865	49.1	0	10.8	8.2	$272,594	$19,345	$253,249
Com 50% and Resi 50%	PLM (graded flat)	PV-only	17,794	3854.2		$10,663,470	$0.088	$337,168	$4,753,646	51.6	0	10.0	8.7	$290,107	$110	$289,996
Com DR 2 to 6PM	TOU	PV-only	18,957	5208.3		$12,471,610	$0.099	$349,548	$6,344,792	64.2	0	11.0	8.1	$417,243	$38,217	$379,026
Com DR 2 to 6PM	PLM (graded flat)	PV-only	18,957	6041.6		$9,813,842	$0.078	$142,053	$7,323,959	68.1	0	12.7	7.2	$542,136	$215	$541,922

Addition of storage changes dynamics somewhat. In a commercial load profile setting, the majority of energy consumption is in the afternoon of a typical 9 hour weekday with 2/3rd in the afternoon and 1/3rd in the morning. A TOU rate presents the highest rate during this afternoon period both in terms of energy and demand rate. Higher penetration of reasonably priced ESS can help in this peak shifting. Since the benefits are felt more for the profile on a demand-based TOU structure than for a PLM structure, simulations result in a considerably larger ESS system for a TOU structure than for the tiered flat rate PLM tariff.

The greatest benefit of storage is seen for a mixed profile of commercial plus residential where a substantial storage system of almost 3 MWh in an almost 50% total utility bill savings over a PV-only solution. This could be attributed to a more even load profile through the full day in which storage can distribute the PV generated energy for use throughout the day. For a residential portfolio, a modest sized ESS does result in a fair savings in operating cost. As expected, a commercial load profile with demand response results in a somewhat smaller ESS (than without DR). For a PLM tariff, simulations result in the minimum amount of storage for a PV+ESS category regardless of load profile.

Table 10: PV+ESS comparisons

		Architecture				*Cost*				*System*		*Economics*				
Building Mix	**Rate Schedule**	***Option***	**Average Load (kWh/day)**	**PV Size (kW)**	**ESS Size (kWh)**	**NPC ($)**	**COE ($)**	**Operating Cost ($/yr)**	**Initial Capital ($)**	**Renewable Fraction (%)**	**N/A**	**IRR (%)**	**Simple Payback (yr)**	**Utility Bill Savings ($/yr)**	**Demand Charge Savings ($/yr)**	**Energy Charge Savings ($/yr)**
Commercial	TOU	PV+210kWh ESS (TESLA)	19,225	5744	1260	$12,460,070	$0.096	$287,307	$7,424,194	70.9	0	11.0	7.7	$516,537	$87,000	$429,537
Commercial	PLM (graded flat)	PV+210kWh ESS (TESLA)	19,225	6255	210	$9,986,756	$0.076	$133,337	$7,649,655	70.0	0	12.2	7.3	$553,042	$259	$552,784
Residential	TOU	PV+210kWh ESS (TESLA)	16,362	1384.55	420	$10,543,240	$0.096	$487,305	$2,001,845	23.2	0	7.1	11.8	$107,080	$19,102	$87,978
Residential	PLM (graded flat)	PV+210kWh ESS (TESLA)	16,362	416.7	210	$11,351,390	$0.108	$609,692	$664,815	9.7	0	7.6	11.5	$39,618	$43	$39,575
Com 50% and Resi 50%	TOU	PV+210kWh ESS (TESLA)	17,794	3730.7	2940	$11,047,620	$0.093	$307,457	$5,658,569	58.2	0	9.4	7.8	$399,753	$85,570	$314,184
Com 50% and Resi 50%	PLM (graded flat)	PV+210kWh ESS (TESLA)	17,794	3901.5	210	$10,701,180	$0.089	$331,866	$4,884,290	52.5	0	9.8	8.8	$297,503	$119	$297,384
Com DR 2 to 6PM	TOU	PV+210kWh ESS (TESLA)	18,957	5000	630	$12,453,620	$0.100	$349,651	$6,325,000	65.1	0	11.1	7.8	$434,296	$49,792	$384,503
Com DR 2 to 6PM	PLM (graded flat)	PV+210kWh ESS (TESLA)	18,957	6175.5	210	$9,813,273	$0.078	$128,769	$7,556,231	69.4	0	12.4	7.2	$554,866	$229	$554,638

Adding storage only (without renewables) does not yield favorable economics compared to business as usual (Table 11). However, for the mixed building profile some amount of storage can result in favorable demand charge savings.

Table 11: ESS-Only Comparisons

Building Mix	Rate Schedule	*Option*	Average Load (kWh/day)	PV Size (kW)	ESS Size (kWh)	NPC ($)	COE ($)	Operating Cost ($/yr)	Initial Capital ($)	Renewable Fraction (%)	N/A	IRR (%)	Simple Payback (yr)	Utility Bill Savings ($/yr)	Demand Charge Savings ($/yr)	Energy Charge Savings ($/yr)
Residential	TOU	ESS-only (100kWh)	16,362		200	$11,036,870	$0.105	$625,113	$80,000	0.0	0	12.1	5.2	$14,188	$13,429	$759
Residential	TOU	ESS-only (210kWh TESLA)	16,362		210	$11,154,550	$0.107	$632,112	$75,000	0.0	0			$6,242	$4,494	$1,748
Residential	PLM (graded flat)	ESS-only (100kWh)	16,362		200	$11,382,570	$0.109	$644,836	$80,000	0.0	0	24.0	3.5	$20,424	$61	$20,363
Residential	PLM (graded flat)	ESS-only (210kWh TESLA)	16,362		210	$11,589,310	$0.111	$656,916	$75,000	0.0	0			$7,397	$22	$7,375
Com 50% and Resi 50%	TOU	ESS-only (100kWh)	17,794		1000	$13,728,610	$0.121	$760,426	$400,000	0.0	0			$42,575	$39,992	$2,584
Com 50% and Resi 50%	TOU	ESS-only (210kWh TESLA)	17,794		210	$13,627,860	$0.120	$773,219	$75,000	0.0	0			$6,216	$4,467	$1,749
Com 50% and Resi 50%	PLM (graded flat)	ESS-only (100kWh)	17,794		300	$12,918,170	$0.113	$730,162	$120,000	0.0	0	20.5	3.9	$27,646	$90	$27,556
Com 50% and Resi 50%	PLM (graded flat)	ESS-only (210kWh TESLA)	17,794		210	$13,173,550	$0.116	$747,300	$75,000	0.0	0			$6,734	$22	$6,712
Com DR 2 to 6PM	TOU	ESS-only (100kWh)	18,957		100	$16,361,250	$0.135	$931,162	$40,000	0.0	0			$1,967	$1,918	$49
Com DR 2 to 6PM	TOU	ESS-only (210kWh TESLA)	18,957		210	$16,421,390	$0.135	$932,596	$75,000	0.0	0			$2,413	$767	$1,646
Com DR 2 to 6PM	PLM (graded flat)	ESS-only (100kWh)	18,957		100	$15,306,210	$0.126	$870,970	$40,000	0.0	0	2.8	7.5	$5,071	$28	$5,043
Com DR 2 to 6PM	PLM (graded flat)	ESS-only (210kWh TESLA)	18,957		210	$15,399,980	$0.127	$874,322	$75,000	0.0	0			$3,598	$21	$3,577

All scenarios are compared side by side with the various metrics such net present cost, effective blended COE, and operating costs in figures 23, 24, and 25.

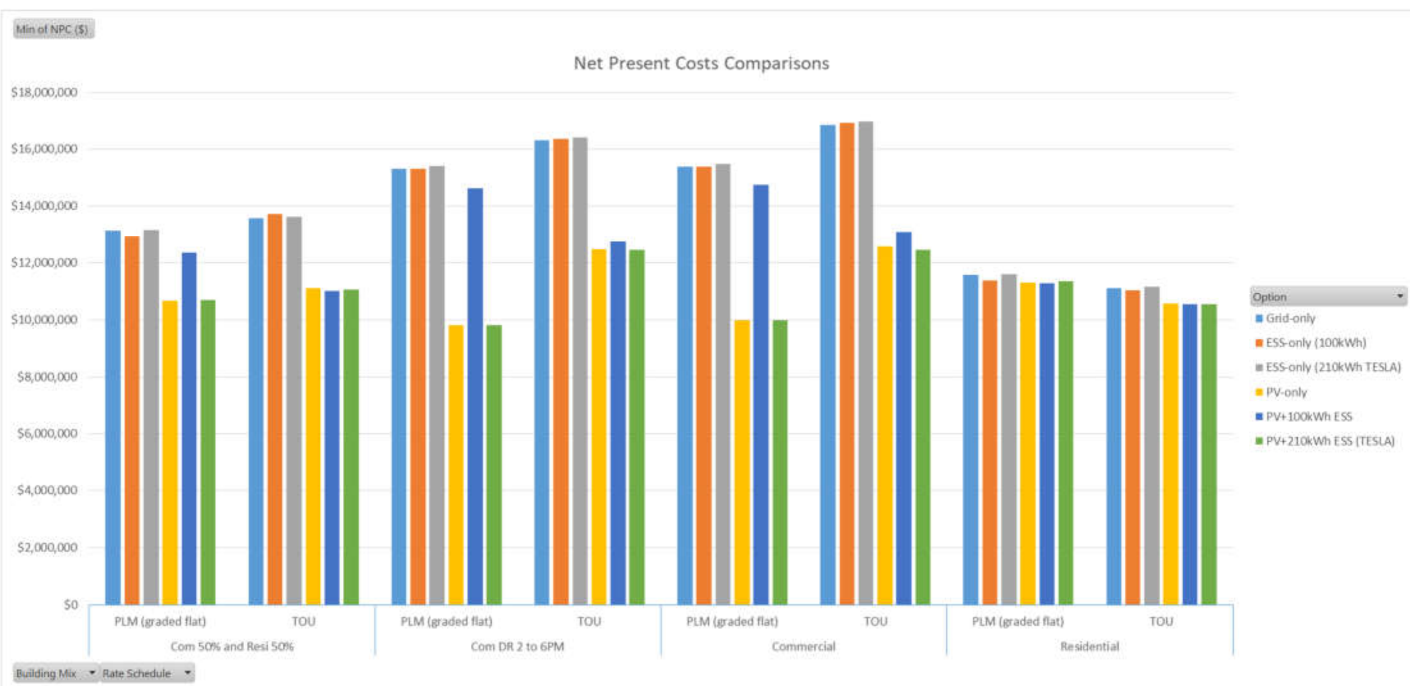

Figure 23: Net Present Cost Comparisons

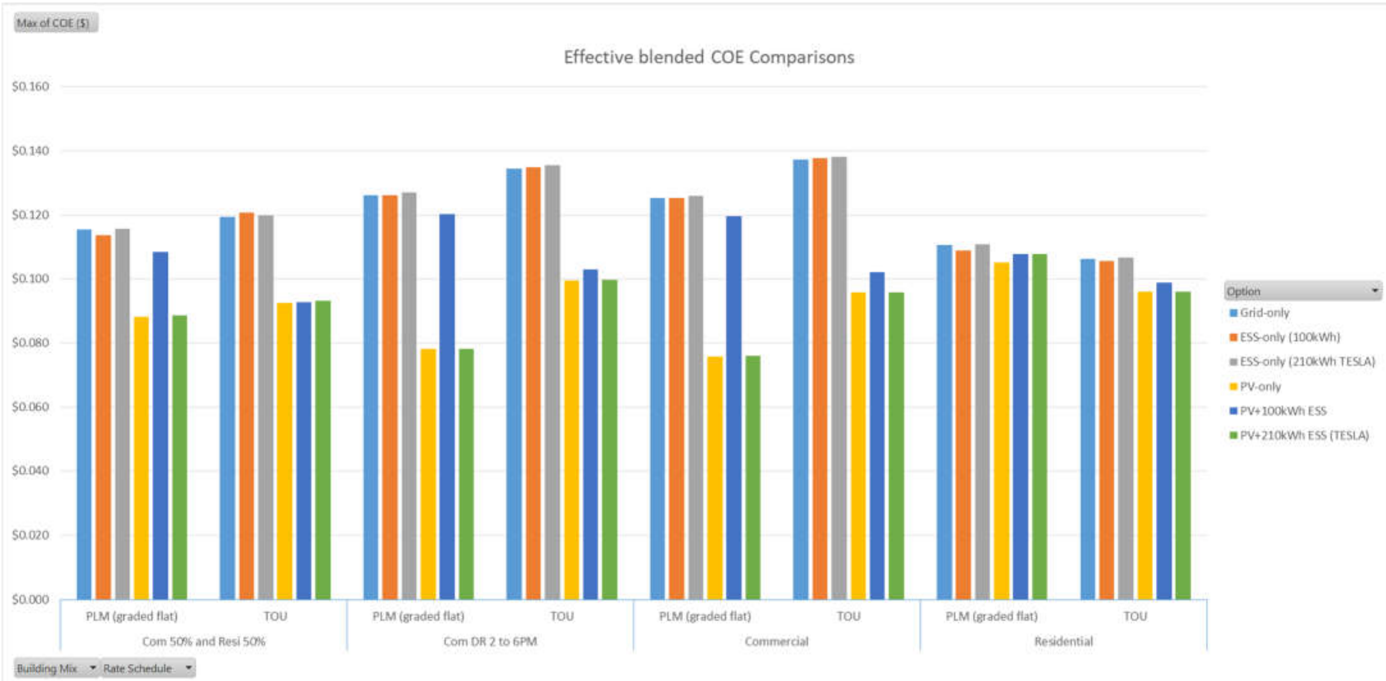

Figure 24: Effective Blended COE Comparisons

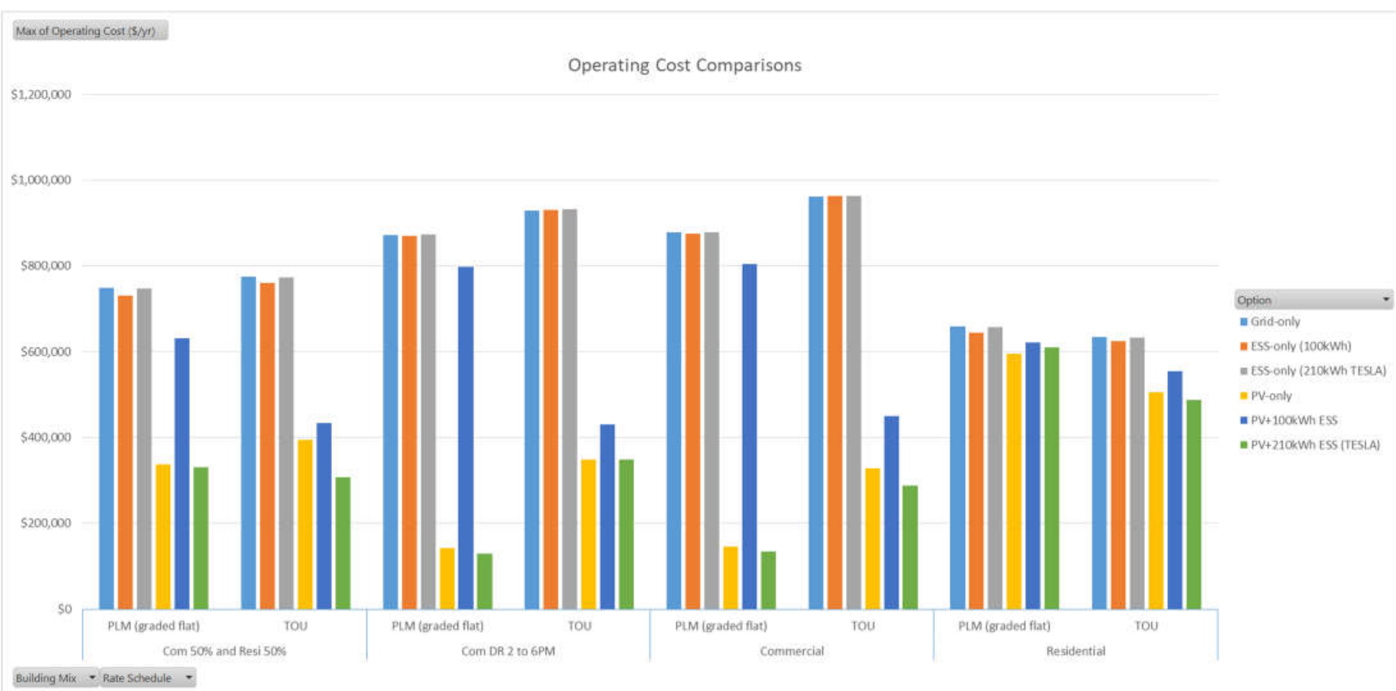

Figure 25: Operating Cost Comparisons

Utility bill savings are shown aggregate (Figure 26) and then further divided into demand savings (Figure 27) and energy savings (Figure 28).

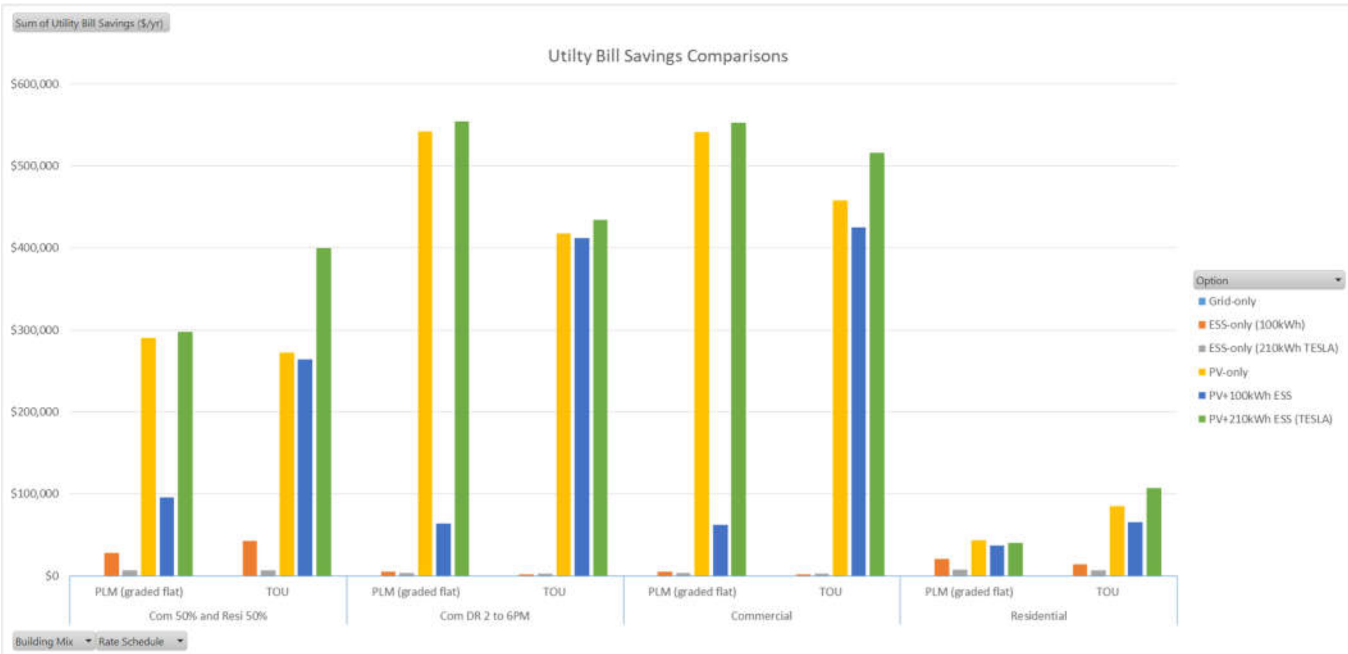

Figure 26: Utility Bill Savings Comparisons

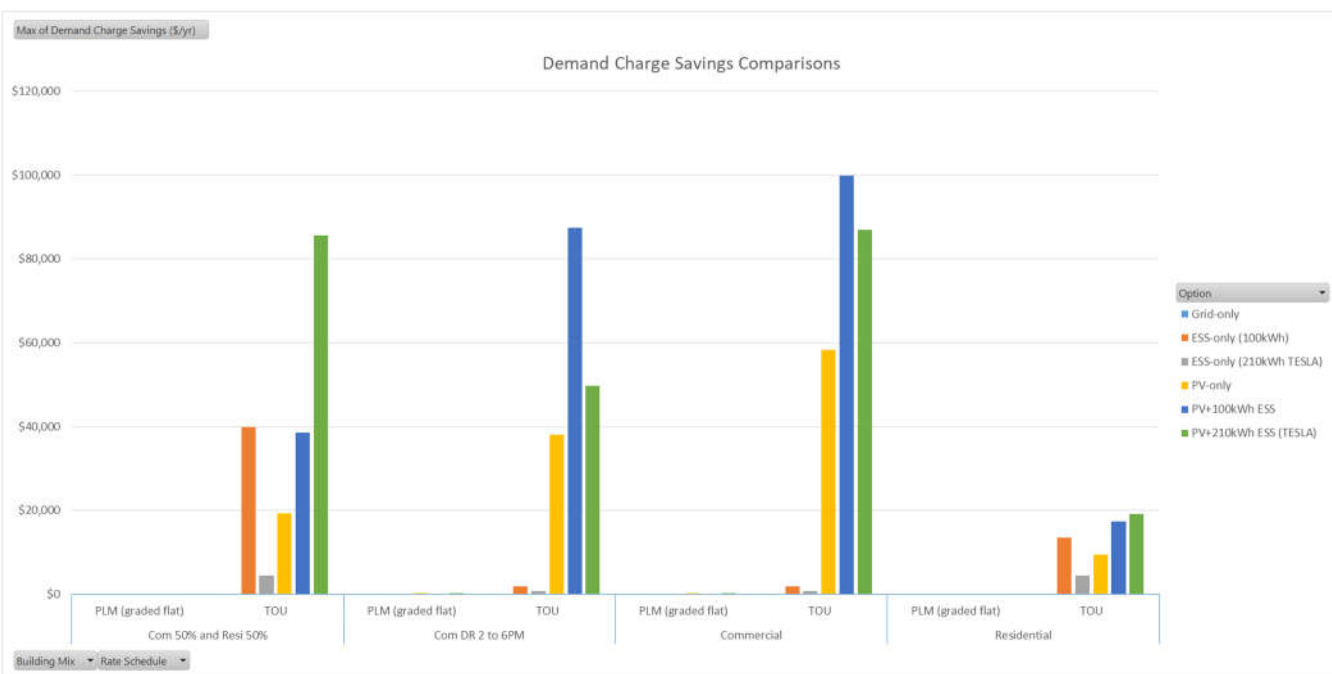

Figure 27: Demand Charge Savings Comparisons

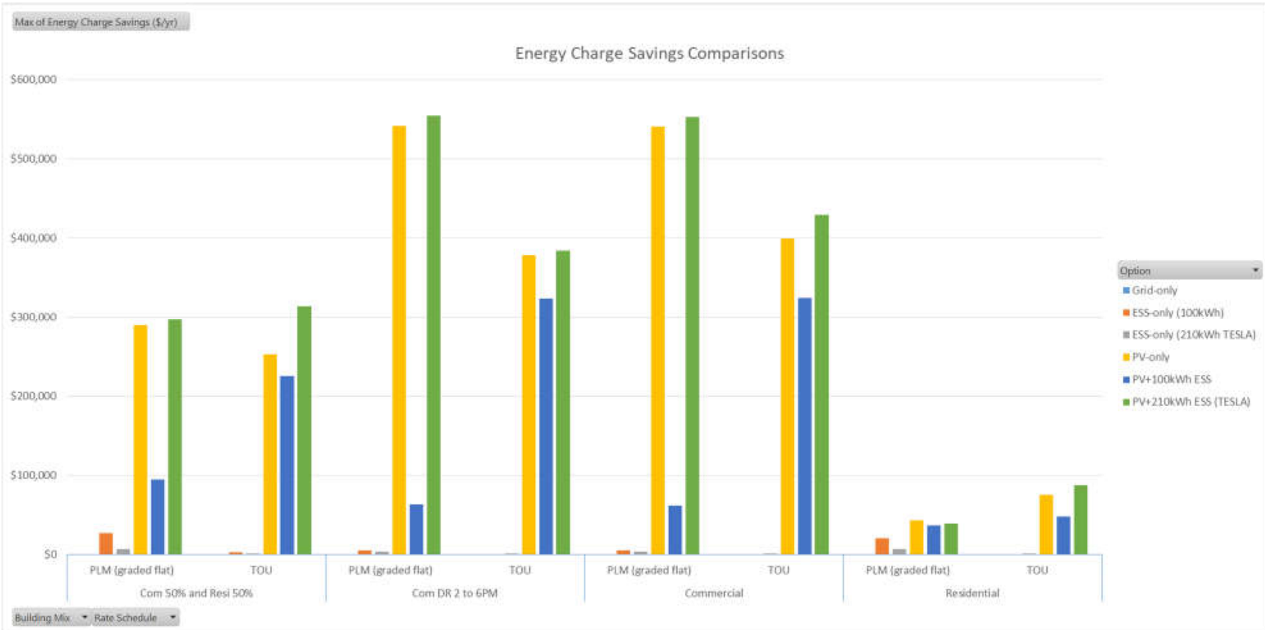

Figure 28: Energy Charge Savings Comparisons

Table 12 presents the full simulation results.

Table 12: Full Simulation Results

			Architecture			Cost				System		Economics				
Building Mix	Rate Schedule	*Option*	Average Load (kWh/day)	PV Size (kW)	ESS Size (kWh)	NPC ($)	COE ($)	Operating Cost ($/yr)	Initial Capital ($)	Renewable Fraction (%)	N/A	IRR (%)	Simple Payback (yr)	Utility Bill Savings ($/yr)	Demand Charge Savings ($/yr)	Energy Charge Savings ($/yr)
Commercial	TOU	Grid-only	19,225			$16,865,980	$0.137	$962,240	$0	0.0	0			$0	$0	$0
Commercial	TOU	PV-only	19,225	5625		$12,574,490	$0.096	$327,486	$6,834,375	66.6	0	11.3	7.9	$458,487	$58,364	$400,123
Commercial	TOU	ESS-only (100kWh)	19,225		100	$16,921,060	$0.138	$963,100	$40,000	0.0	0			$1,967	$1,918	$49
Commercial	TOU	ESS-only (210kWh TESLA)	19,225		210	$16,980,280	$0.138	$964,482	$75,000	0.0	0			$2,465	$818	$1,647
Commercial	TOU	PV+100kWh ESS	19,225	3750	1400	$13,081,380	$0.102	$450,149	$5,191,250	54.9	0	11.9	7.0	$424,940	$100,033	$324,907
Commercial	TOU	PV+210kWh ESS (TESLA)	19,225	5744	1260	$12,460,070	$0.096	$287,307	$7,424,194	70.9	0	11.0	7.7	$516,537	$87,000	$429,537
Commercial	PLM (graded flat)	Grid-only	19,225			$15,396,290	$0.125	$878,391	$0	0.0	0			$0	$0	$0
Commercial	PLM (graded flat)	PV-only	19,225	6145.8		$9,984,388	$0.076	$144,800	$7,446,354	68.8	0	12.4	7.3	$541,378	$247	$541,131
Commercial	PLM (graded flat)	ESS-only (100kWh)	19,225		100	$15,395,670	$0.125	$876,074	$40,000	0.0	0	3.1	7.4	$5,144	$28	$5,117
Commercial	PLM (graded flat)	ESS-only (210kWh TESLA)	19,225		210	$15,490,940	$0.126	$879,512	$75,000	0.0	0			$3,586	$21	$3,565
Commercial	PLM (graded flat)	PV+100kWh ESS	19,225	437	100	$14,753,690	$0.120	$804,192	$657,946	8.7	0	14.9	6.0	$61,855	$73	$61,782
Commercial	PLM (graded flat)	PV+210kWh ESS (TESLA)	19,225	6255	210	$9,986,756	$0.076	$133,337	$7,649,655	70.0	0	12.2	7.3	$553,042	$259	$552,784
Residential	TOU	Grid-only	16,362			$11,106,450	$0.106	$633,646	$0	0.0	0			$0	$0	$0
Residential	TOU	PV-only	16,362	1250		$10,563,910	$0.096	$506,062	$1,693,750	21.1	0	7.5	10.8	$85,261	$9,488	$75,773
Residential	TOU	ESS-only (100kWh)	16,362		200	$11,036,870	$0.105	$625,113	$80,000	0.0	0	12.1	5.2	$14,188	$13,429	$759
Residential	TOU	ESS-only (210kWh TESLA)	16,362		210	$11,154,550	$0.107	$632,112	$75,000	0.0	0			$6,242	$4,494	$1,748
Residential	TOU	PV+100kWh ESS	16,362	524.5	200	$10,547,320	$0.099	$554,989	$819,569	11.9	0	11.5	7.3	$65,576	$17,414	$48,162
Residential	TOU	PV+210kWh ESS (TESLA)	16,362	1384.55	420	$10,543,240	$0.096	$487,305	$2,001,845	23.2	0	7.1	11.8	$107,080	$19,102	$87,978
Residential	PLM (graded flat)	Grid-only	16,362			$11,561,440	$0.110	$659,605	$0	0.0	0			$0	$0	$0
Residential	PLM (graded flat)	PV-only	16,362	625		$11,307,300	$0.105	$594,947	$879,167	13.7	0	7.1	11.2	$43,377	$33	$43,344
Residential	PLM (graded flat)	ESS-only (100kWh)	16,362		200	$11,382,570	$0.109	$644,836	$80,000	0.0	0	24.0	3.5	$20,424	$61	$20,363
Residential	PLM (graded flat)	ESS-only (210kWh TESLA)	16,362		210	$11,589,310	$0.111	$656,916	$75,000	0.0	0			$7,397	$22	$7,375
Residential	PLM (graded flat)	PV+100kWh ESS	16,362	208.3	200	$11,279,560	$0.108	$621,817	$380,463	4.9	0	12.2	6.6	$37,039	$71	$36,968
Residential	PLM (graded flat)	PV+210kWh ESS (TESLA)	16,362	416.7	210	$11,351,390	$0.108	$609,692	$664,815	9.7	0	7.6	11.5	$39,618	$43	$39,575
Com 50% and Resi 50%	TOU	Grid-only	17,794			$13,579,300	$0.119	$774,728	$0	0.0	0			$0	$0	$0
Com 50% and Resi 50%	TOU	PV-only	17,794	3385.4		$11,116,410	$0.092	$394,433	$4,202,865	49.1	0	10.8	8.2	$272,594	$19,345	$253,249
Com 50% and Resi 50%	TOU	ESS-only (100kWh)	17,794		1000	$13,728,610	$0.121	$760,426	$400,000	0.0	0			$42,575	$39,992	$2,584
Com 50% and Resi 50%	TOU	ESS-only (210kWh TESLA)	17,794		210	$13,627,860	$0.120	$773,219	$75,000	0.0	0			$6,216	$4,467	$1,749
Com 50% and Resi 50%	TOU	PV+100kWh ESS	17,794	2604.2	630	$10,997,210	$0.093	$433,158	$3,404,896	43.7	0	12.6	7.0	$264,512	$38,680	$225,833
Com 50% and Resi 50%	TOU	PV+210kWh ESS (TESLA)	17,794	3730.7	2940	$11,047,620	$0.093	$307,457	$5,658,569	58.2	0	9.4	7.8	$399,753	$85,570	$314,184
Com 50% and Resi 50%	PLM (graded flat)	Grid-only	17,794			$13,134,070	$0.115	$749,327	$0	0.0	0			$0	$0	$0
Com 50% and Resi 50%	PLM (graded flat)	PV-only	17,794	3854.2		$10,663,470	$0.088	$337,168	$4,753,646	51.6	0	10.0	8.7	$290,107	$110	$289,996
Com 50% and Resi 50%	PLM (graded flat)	ESS-only (100kWh)	17,794		300	$12,918,170	$0.113	$730,162	$120,000	0.0	0	20.5	3.9	$27,646	$90	$27,556
Com 50% and Resi 50%	PLM (graded flat)	ESS-only (210kWh TESLA)	17,794		210	$13,173,550	$0.116	$747,300	$75,000	0.0	0			$6,734	$22	$6,712
Com 50% and Resi 50%	PLM (graded flat)	PV+100kWh ESS	17,794	833.3	300	$12,364,750	$0.108	$631,922	$1,288,519	17.9	0	10.5	7.8	$95,382	$108	$95,273
Com 50% and Resi 50%	PLM (graded flat)	PV+210kWh ESS (TESLA)	17,794	3901.5	210	$10,701,180	$0.089	$331,866	$4,884,290	52.5	0	9.8	8.8	$297,503	$119	$297,384
Com DR 2 to 6PM	TOU	Grid-only	18,957			$16,306,170	$0.134	$930,301	$0	0.0	0			$0	$0	$0
Com DR 2 to 6PM	TOU	PV-only	18,957	5208.33333		$12,471,610	$0.099	$349,548	$6,344,792	64.2	0	11.0	8.1	$417,243	$38,217	$379,026
Com DR 2 to 6PM	TOU	ESS-only (100kWh)	18,957		100	$16,361,250	$0.135	$931,162	$40,000	0.0	0			$1,967	$1,918	$49
Com DR 2 to 6PM	TOU	ESS-only (210kWh TESLA)	18,957		210	$16,421,390	$0.135	$932,596	$75,000	0.0	0			$2,413	$767	$1,646
Com DR 2 to 6PM	TOU	PV+100kWh ESS	18,957	3750	1400	$12,752,880	$0.103	$431,407	$5,191,250	55.0	0	11.4	7.3	$411,465	$87,476	$323,989
Com DR 2 to 6PM	TOU	PV+210kWh ESS (TESLA)	18,957	5000	630	$12,453,620	$0.100	$349,651	$6,325,000	65.1	0	11.1	7.8	$434,296	$49,792	$384,503
Com DR 2 to 6PM	PLM (graded flat)	Grid-only	18,957			$15,305,530	$0.126	$873,213	$0	0.0	0			$0	$0	$0
Com DR 2 to 6PM	PLM (graded flat)	PV-only	18,957	6041.66667		$9,813,842	$0.078	$142,053	$7,323,959	68.1	0	12.7	7.2	$542,136	$215	$541,922
Com DR 2 to 6PM	PLM (graded flat)	ESS-only (100kWh)	18,957		100	$15,306,210	$0.126	$870,970	$40,000	0.0	0	2.8	7.5	$5,071	$28	$5,043
Com DR 2 to 6PM	PLM (graded flat)	ESS-only (210kWh TESLA)	18,957		210	$15,399,980	$0.127	$874,322	$75,000	0.0	0			$3,598	$21	$3,577
Com DR 2 to 6PM	PLM (graded flat)	PV+100kWh ESS	18,957	436.921296	100	$14,627,460	$0.120	$796,991	$657,946	8.8	0	15.4	5.8	$63,880	$74	$63,806
Com DR 2 to 6PM	PLM (graded flat)	PV+210kWh ESS (TESLA)	18,957	6175.51523	210	$9,813,273	$0.078	$128,769	$7,556,231	69.4	0	12.4	7.2	$554,866	$229	$554,638

CHAPTER 8. CONCLUSION AND FUTURE WORK

For grid-tied microgrids that consist of predominantly commercial loads, the addition of photovoltaics can result in substantial savings in net present cost and HOMER COE values. The benefits however dependent heavily on the tariff and its effect on cost of electricity as considered monthly throughout the year rather than at specific peak periods. If a tariff is flat (or tiered flat) such that if the electricity cost is even throughout the year then the addition of PV can be substantial in lowering the net present cost compared to business as usual. This delta could be greater than the net present cost reduction from a time of use tariff that has high rates during peak months and peak hours but lower costs throughout the year.

Addition of an energy storage system along with PV results in further benefits in almost all scenarios. However, these benefits are not quite as pronounced as expected. Cost of energy storage is set currently on the lower side of what's available at $400/kWh. Many ESS come in closer to $1000/kWh. At this higher price ESS makes sense to offset diesel generators and the like but not so much in standard grid-tie situations. Even at the lower cost of $400/kWh, the benefits to grid-tie system are marginal. However, in the case of a time of use rate that is paired with a mixed load profile (e.g. commercial and residential), significant savings can be had on the demand portion of the load. Further research can be done to see at what price point (perhaps $200/kWh or less) does ESS make a significant reduction in net present cost.

With current prices for storage, ESS alone without PV does not merit any financial benefit.

Deriving a methodology for optimizing a microgrid resources entails considering numerous factors:

- The rate tariff structure
- Pricing on PV
- Pricing on ESS
- Load profile structure

The more the load profile is distributed throughout the day especially outside of main solar PV production hours, the greater the benefit a ESS can have especially in the case of a TOU tariff. However, a larger PV system can yield greater savings for a system whose electricity cost is more evenly distributed throughout the year (such as in the case a tiered flat tariff such as PLM).

Future work will include the addition of EV charging stations and how different approaches to charging affect the optimization of the microgrid. Such approaches could take the following form:

1. Grouping all charging together such charging is continuous with all cars starting at 9 AM in the morning until noon
2. Distributing the charging throughout the day, such that half the cars from 9 AM until noon and the other half charge in the afternoon from 2 PM to 5PM.
3. Charging of each car spread out with half the "tank" charged from 9 AM to noon (at half rate) and the other half charged from 2 PM to 5 PM (at half rate).

Additional research can be carried out on the effect of load profile mixes on different topologies such as "smart village" and "smart island".

APPENDIX A. DEPARTMENT OF ENERGY BUILDING PROFILES

Reference	https://www.energy.gov/eere/buildings/commercial-reference-buildings					
	https://www.nrel.gov/docs/fy11osti/46861.pdf					
Location	Atlanta, GA					
BUILDING NUMBER	**BUILDING CATEGORY**	**BUILDING TYPE NAME**	**TOTAL FLOOR AREA (FT^2)**	**TOTAL FLOOR AREA (M^2)**	**NUMBER OF FLOORS**	**ANNUAL LOAD (FROM DOE) (kWh)**
1	Commercial	Large Office	498,588	46,320	12	
2	Commercial	Medium Office	53,628	4,982	3	1,392,358
3	Commercial	Small Office	5,500	511	1	
4	Commercial	Warehouse	52,045	4,835	1	
5	Retail	Stand-alone Retail	24,962	2,319	1	
6	Retail	Strip Mall	22,500	2,090	1	
7	Educational	Primary School	73,960	6,871	1	
8	Educational	Secondary School	210,887	19,592	2	
9	Retail	Supermarket	45,000	4,181	1	
10	Retail	Quick Service Restaurant	2,500	232	1	
11	Retail	Full Service Restaurant	5,500	511	1	
12	Medical	Hospital	241,351	22,422	5	
13	Medical	Outpatient Health Care	40,946	3,804	3	
14	Civil	Small Hotel	43,200	4,013	4	
15	Civil	Large Hotel	122,120	11,345	6	
16	Commercial	Midrise Apartment	33,740	3,135	4	494,182

APPENDIX B. GEORGIA POWER PLM-11 TARIFF

ELECTRIC SERVICE TARIFF:

POWER AND LIGHT MEDIUM
SCHEDULE: “PLM-11”

GEORGIA POWER
A SOUTHERN COMPANY

PAGE	EFFECTIVE DATE	REVISION	PAGE NO.
1 of 3	With Bills Rendered for the Billing Month of January, 2016	Original	4.00

AVAILABILITY:

Throughout the Company's service area from existing lines of adequate capacity.

APPLICABILITY:

To all electric service of one standard voltage required on the customer's premises, delivered at one point and metered at or compensated to that voltage for any customer with a demand, as determined under the Special Applicability Provisions, of not less than 30 kW but less than 500 kW.

TYPE OF SERVICE:

Single or three phase, 60 hertz, at a standard voltage.

MONTHLY RATE:

Energy Charge Including Demand Charge

Basic Service Charge $19.00

All consumption (kWh) not greater than 200 hours times the billing demand:
First 3,000 kWh...11.2561¢ per kWh
Next 7,000 kWh ....10.3091¢ per kWh
Next 190,000 kWh ....8.8885¢ per kWh
Over 200,000 kWh...6.8955¢ per kWh

All consumption (kWh) in excess of 200 hours and not greater than 400 hours times the billing demand.................................1.1437¢ per kWh

All consumption (kWh) in excess of 400 hours and not greater than 600 hours times the billing demand.................................0.8606¢ per kWh

All consumption (kWh) in excess of 600 hours times the billing demand.................................0.7486¢ per kWh

Minimum Monthly Bill:

A. $19.00 Basic Service Charge plus $8.24 per kW of billing demand in excess of 30 kW, plus excess kVAR charges, plus Environmental Compliance Cost Recovery, plus Nuclear Construction Cost Recovery, plus appropriate Demand Side Management Schedule, plus Fuel Cost Recovery as applied to the current month kWh, plus Municipal Franchise Fee.

B. Metered Outdoor Lighting: The lesser of (1) that determined from paragraph "A" above, or (2) $42.44 per meter plus Environmental Compliance Cost Recovery, plus Nuclear Construction Cost Recovery, plus appropriate Demand Side Management Schedule, plus Fuel Cost Recovery, plus Municipal Franchise Fee for metered outdoor lighting installations, provided service is limited to the lighting equipment itself and such incidental load as may be required to operate coincidentally with the lighting equipment.

APPENDIX C. GEORGIA POWER TOU-GSD-10 TARIFF

ELECTRIC SERVICE TARIFF:

TIME OF USE - GENERAL SERVICE DEMAND SCHEDULE: "TOU-GSD-10"

GEORGIA POWER
A SOUTHERN COMPANY

PAGE	EFFECTIVE DATE	REVISION	PAGE NO.
1 of 3	With Bills Rendered for the Billing Month of January, 2016	Original	4.10

AVAILABILITY:

Throughout the Company's service area from existing lines of adequate capacity

APPLICABILITY:

To all electric service for Commercial and Industrial customers, at one standard voltage required on the customer's premises, delivered at one point and metered at or compensated to that voltage.

TYPE OF SERVICE:

Single or three phase, 60 hertz, and at a standard voltage.

MONTHLY RATE:

Basic Service Charge..$209.00

Energy Charges:

- **On-Peak kWh...12.2372¢ per kWh**
- **Shoulder kWh...6.2514¢ per kWh**
- **Off-Peak kWh...2.3541¢ per kWh**

Demand Charges:

- **On-Peak kW...$15.66 per kW**
- **Economy kW...$5.23 per kW**
- **Maximum kW...$5.23 per kW**

Minimum Monthly Bill: $209.00 Basic Service Charge plus Environmental Compliance Cost Recovery, plus Nuclear Construction Cost Recovery, plus appropriate Demand Side Management Schedule, plus Municipal Franchise Fee.

DETERMINATION OF REACTIVE DEMAND:

Where there is an indication of a power factor of less than Ninety-Five percent (95%) lagging, the Company may at its option, install metering equipment to measure Reactive Demand. The Reactive Demand shall be the highest 30-minute kVAR measurement during the month. The Excess Reactive Demand shall be kVAR which is in excess of one-third of the measured actual kW in the current month. Each month the Company will bill excess kVAR at the rate of $0.29 per excess kVAR.

ENVIRONMENTAL COMPLIANCE COST RECOVERY:

The amount calculated at the above rate will be increased under the provisions of the Company's effective Environmental Compliance Cost Recovery Schedule, including any applicable adjustments.

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